Kaon and pion femtoscopy at top RHIC energy in hydrokinetic model [1]

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Abstract

The hydrokinetic model is applied to restore the initial conditions and space-time picture of the matter evolution in central Au+Au collisions at the top RHIC energy. The analysis is based on the detailed reproduction of the pion and kaon momentum spectra and femtoscopic data in whole interval of the transverse momenta studied by both STAR and PHENIX collaborations. A good description of the pion and kaon transverse momentum spectra and interferometry radii is reached with both initial energy density profiles motivated by the Glauber and Color Glass Condensate (CGC) models, however, at different energy densities.

1 Introduction

In this letter we apply the HydroKinetic Model (HKM) proposed in [1, 2] and further developed in [3, 4, 5] to an analysis of the femtoscopic measurements at RHIC for central Au+Au collisions at the top energy $\sqrt{s} = 200$ AGeV. Namely, we analyze pion and kaon transverse momentum spectra and the m_T-behavior of the pion and kaon interferometry radii to clarify, in particularly, how these observables depend on the initial conditions: Glauber and CGC-like.

Hydrokinetic approach combines the advantages of the hydrodynamic approximation, where possible phase transitions are encoded in the corresponding equation of state (EoS), and microscopic approach, accounting for a non-equilibrated process of the spectra formation due to gradual particle liberation. The dynamical decoupling is described by the particle escape probabilities in inhomogeneous hydrodynamically expanding systems in the way consistent with the kinetic equations in the relaxation time approximation for emission function. The basic hydrokinetic code, proposed in [2], is modified now to include decays of resonances into the expanding hadronic

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chemically non-equilibrated system and, based on the resulting composition of the hadron-resonance gas at each space-time point, to calculate the equation of state (EoS) in a vicinity of this point. The obtained local EoS allows one to determine the further evolution of the considered fluid elements.

2 Model description and results

Let us briefly describe the main features of the model. Our results are all related to the central rapidity slice where we use the boost-invariant Bjorken-like initial condition in longitudinal direction.

Initial conditions: Two models of initial conditions for hydrodynamic expansion were used: Glauber model and CGC-like model. In former one, initial energy density in the transverse plane is proportional to the participant nucleon density[8]. For CGC model, the procedure described in [4, 7] give us the energy profile in the transverse plane:

$$\epsilon(x_T) = \epsilon_0 \frac{\rho^{3/2}(0, x_T)}{\rho_0^{3/2}}, \tag{1}$$

where the number of participants ρ is defined in the same way as in Glauber model. The parameter $\epsilon_0 \equiv \epsilon(b = 0, \mathbf{x}_T = 0)$ – the maximal energy density at the initial moment of thermalization – is the first fitting parameter of HKM for both IC cases.

Following the ideas about the pre-thermal flow development [7] we take a "conventional" proper-time of thermalization, τ_i =1 fm/c and non-zero transverse flow already developed at the thermalization time. The initial transverse rapidity profile is supposed to be linear in radius r_T:

$$y_T = \alpha \frac{r_T}{R_T}, \quad \text{where} \quad R_T = \sqrt{< r_T^2 >}, \tag{2}$$

here α is the second fitting parameter in our model. Note that the fitting parameter α should include also a positive correction for underestimated resulting transverse flow since in this work we did not account in direct way for the viscosity effects [6] neither at QGP stage nor at hadronic one. In formalism of HKM [2] the viscosity effects at hadronic stage are incorporated in the mechanisms of the back reaction of particle emission on hydrodynamic evolution which we ignore in current calculations. Since the corrections to transverse flows which depend on unknown viscosity coefficients are unknown, we use fitting parameter α to describe the "additional unknown portions" of

flows, caused both factors: by a developing of the pre-thermal flows and the viscosity effects in quark-gluon plasma.

Equation of state: At high temperatures corresponding to the QGP phase and crossover transition to hadron phase we use a realistic EoS [11] adjusted to the lattice QCD results for zero barionic chemical potential so that it is matched with an ideal chemically equilibrated multicomponent hadron resonance gas at $T_c = 175$ MeV. To take into account a conservation of the net baryon number, electric charge and strangeness in the QGP phase, we make corrections to thermodynamic quantities for nonzero chemical potentials, as proposed in [12].

The chemical freeze-out temperature $T_{ch} = 165$ MeV is used, with corresponding chemical potentials μ_B =29 MeV, μ_S =7 MeV, μ_E =-1 MeV and also the strangeness suppression factor $\gamma_S = 0.935$ which are dictated by 200A GeV RHIC particle number ratios analysis done in the statistical model [9, 10].

At the chemical freeze-out temperature T_{ch} the EoS is matched with ideal Boltzmann hadronic resonance gas which includes $N = 359$ hadron states made of u, d, s quarks with masses up to 2.6 GeV (the same set of hadrons as used in [13]). The EoS used at temperatures below chemical freeze-out is chemically non-equilibrated and takes into account the change of chemical composition due to decays of resonances in the form:

$$\partial_\mu(n_i(x)u^\mu(x)) = -\Gamma_i n_i(x) + \sum_j b_{ij}\Gamma_j n_j(x) \tag{3}$$

here one neglects a thermal motion of the resonance j, that can be justified because post (chemical) freeze-out temperatures are much less than the mass of the lightest known resonance. Also, equations for the hydrodynamic evolution are written under supposition of an instant thermalization of the decay products, that is consistent with the ideal fluid approximation (mean free path is zero).

Spectra formation: During the hadron phase, hadrons are permitted to leave the system. The process of particle emission is described by the means of emission function, which, for (quasi-)stable particles is expressed through the gain term $G_i^{\text{gain}}(x,p)$ in Boltzmann equations and escape probabilities [1, 2]. In this formalism, particle emission is formed by the particles that undergo their last interaction or already free initially. Thus, emission depend on the collision rate of given particle with hadron medium, which is calculated in a standard way using the total hadron cross-sections taken in a way similar to that in UrQMD code.

Results and discussion: The results of the HKM for the pion and kaon spectra, interferometry radii and R_{out}/R_{side} ratio are presented in Fig. 1. The best fit for the Glauber IC is reached at the following values of the two fitting parameters related to the proper time $\tau = 1$ fm/c: $\epsilon_0 = 16.5$ GeV/fm^3 ($\langle\epsilon\rangle = 11.69$ GeV/fm^3) and parameter of the initial velocity defined by (2), $\alpha = 0.248$ ($\langle v_T \rangle = 0.224$). In the case of the CGC-like initial conditions $R_T = 3.88$ fm, the fitting parameters leading to the best data description are $\epsilon_0 = 19.5$ GeV/fm^3 ($\langle\epsilon\rangle = 13.22$ GeV/fm^3) and $\alpha = 0.23$ ($\langle v_T \rangle = 0.208$). Since the temperature and baryonic chemical potential at chemical freeze-out, which are taken from the analysis of the particle number ratios [9], are is more suitable for the STAR experiment, the HKM results for kaon spectra are good for the STAR data but not so much for the PHENIX ones. Note also that, in spite of other studies (e.g., [14]), we compare our results for the interferometry radii within the whole measured interval of p_T covered at the top RHIC energy. Finally, one can conclude from Fig. 1 that the description of pion and kaon spectra and space-time scales is quite good for both IC, the Glauber and CGC. It is worth noting, however, that the two fitting parameters α and ϵ_0 are various by 10-20% for different IC, as it is described above.

The special attention acquires a good description of the pion and kaon longitudinal radii altogether with R_{out}/R_{side} ratio, practically, within the experimental errors. Such an achievement means that the HKM catches the main features of the matter evolution in A+A collisions and correctly reproduces the homogeneity lengths in the different parts of the system which are directly related to the interferometry radii at the different momenta of the pairs [15].

3 Conclusions

In this letter, we show how hydro-kinetic model is applied to restore the initial conditions and space-time picture of the matter evolution in central Au+Au collisions at the top RHIC energy. The analysis, which is based on a detailed reproduction of the pion and kaon momentum spectra and measured femtoscopic scales, demonstrates that basically the pictures of the matter evolution and particle emission are similar at both Glauber and CGC initial conditions (IC) with, however, the different initial maximal energy densities: it is about 20% more for the CGC initial conditions. The main factors, which allows one to describe well simultaneously the spectra and femtoscopic

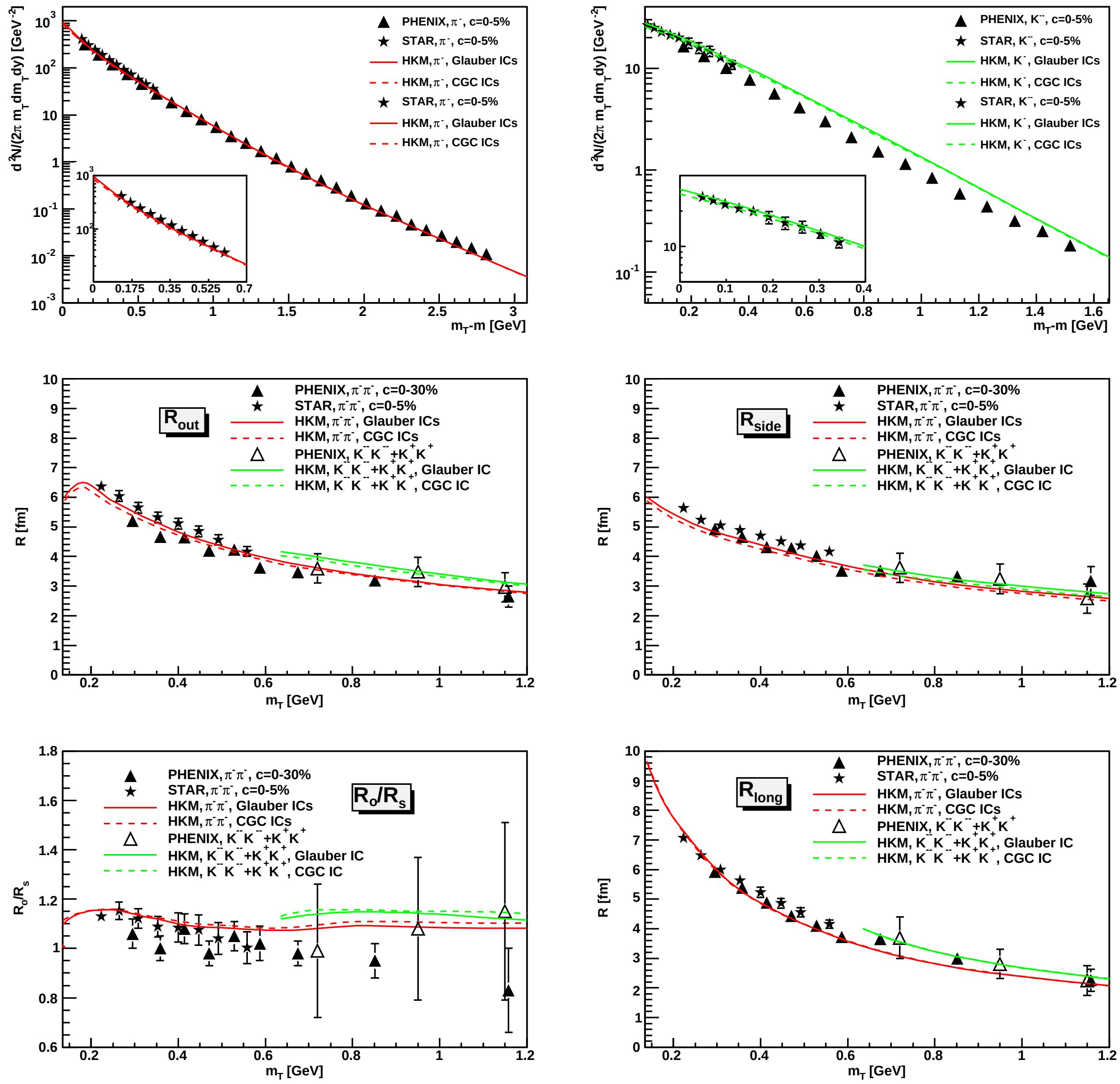

Figure 1: The transverse momentum spectra of negative pions and negative kaons, all calculated in the HKM model. The comparison only with the STAR data are presented in the separate small plots. (Top). The interferometry radii and R_{out}/R_{side} ratio for $\pi^-\pi^-$ pairs and mixture of K^-K^- and K^+K^+ pairs. (Middle and bottom). The experimental data are taken from the STAR [16, 17] and PHENIX [18, 19, 20] Collaborations.

scales are: a relatively hard EoS (crossover transition and chemically non-equilibrium composition of hadronic matter), pre-thermal transverse flows developed to thermalization time, an account for an "additional portion" of the transverse flows due to the shear viscosity effect and fluctuation of initial conditions, a correct description of a gradual decay of the non-equilibrium fluid at the late stage of expansion.

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